MDA Cost Improvement Slope Analysis

Scott M Vickers
MCR Federal, Inc
1111 Jefferson Davis Highway
Arlington, VA 22202
(703)416-9500
svickers@bmdo.mcri.com

DoD Cost Analysis Symposium
Williamsburg, VA
Jan 2003

Contents

- Missile Defense Agency requirement
- Data and normalization procedure
- Model development procedure
- Model forms considered
- Model results
- Estimating Production Costs from EMD Manufacturing Data Using MDA Slopes.
- Questions

MDA Missile Cost Improvement Slope Project Requirements

- Develop Learning Curves that can be used in estimating production costs of missile hardware.
  - Examine CAUC Theory models, Unit Theory models, and the impact of applying production rate adjustments.
  - Determine if it is appropriate to apply a single curve based on total system cost, or if it is better to apply unique curves for major system components.
  - Determine generic curves derived from multiple systems that can be used for a “class” of missile programs.
- Determine how best to model the transition from pre-production manufacturing to production manufacturing.
  - Determine if a step factor is appropriate.
  - Determine if a different slope should be used to estimate pre-production and production costs.
  - Determine if the production unit count should start at one or continue from the last pre-production unit.

Missile Programs Used in the CI Study

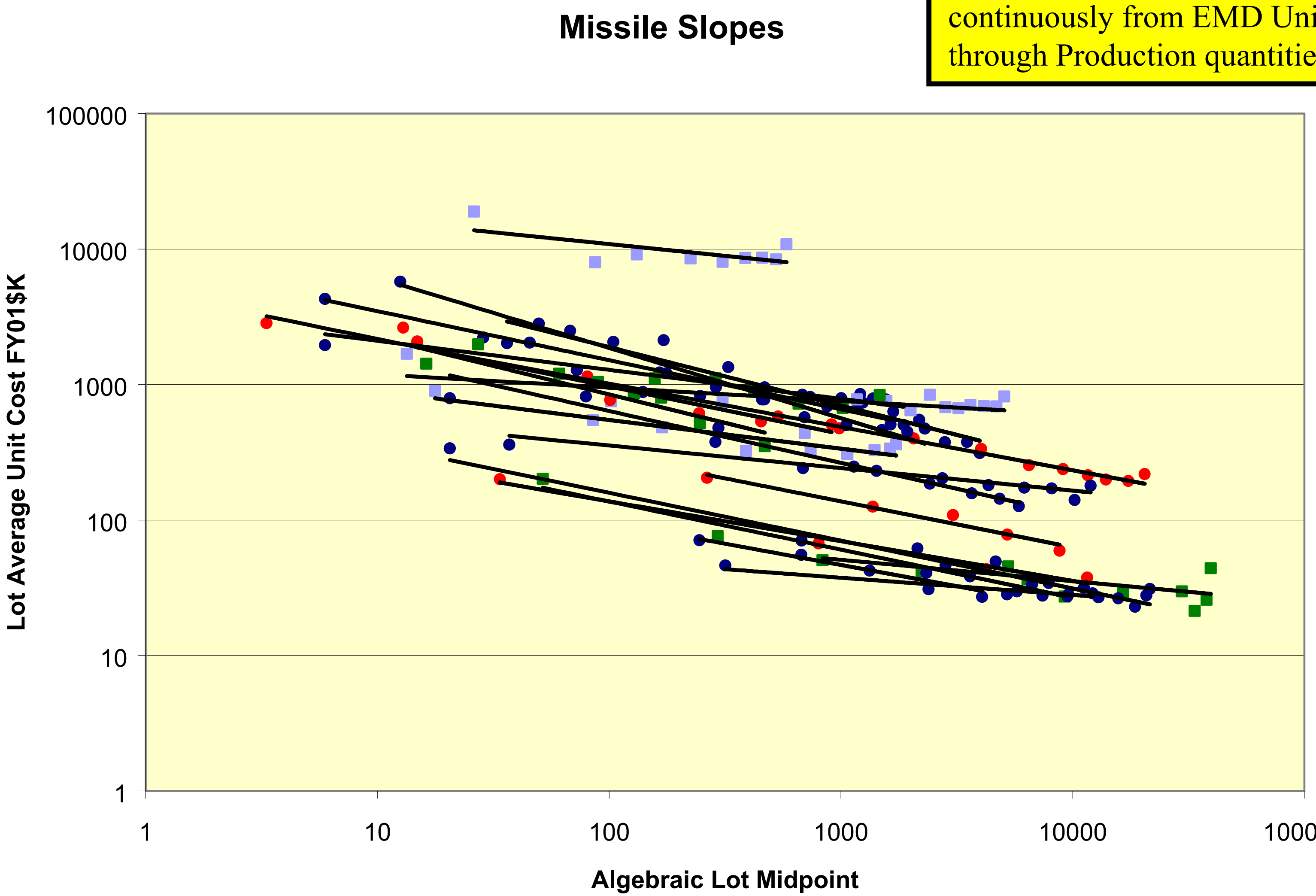
System	Nomenclature	Contractor	Mission Class	Developing Service
AMRAAM	AIM-120	Raytheon	Air to Air	Air Force
AMRAAM	AIM-120	Hughes	Air to Air	Air Force
HARM	AGM-88A/B	TI	Air to Surface	Navy
MAVERICK	AGM-65A/B	Hughes	Air to Surface	Air Force
PHOENIX	AIM-54A	Hughes	Air to Air	Navy
PHOENIX	AIM-54C	Hughes	Air to Air	Navy
STINGER	FIM-92A RMP	GD	Surface to Air	Army
STINGER	FIM-92A	GD	Surface to Air	Army
MAVERICK	AGM-65F	Raytheon	Air to Surface	Air Force
SPARROW	AIM/RIM-7M	Raytheon	Air to Air	Navy
SIDEWINDER	AIM-9M	Ford	Air to Air	Navy
SIDEWINDER	AIM-9M	Raytheon	Air to Air	Navy
SIDEWINDER	AIM-9L	Ford	Air to Air	Navy
SIDEWINDER	AIM-9L	Raytheon	Air to Air	Navy
SPARROW	AIM-7F	Raytheon	Air to Air	Navy
TRIDENT I	UGM-96A	LM	Surface to Surface	Navy
HARPOON	UGM-84	MD	Surface to Surface	Navy
ATACM	MGM-140	LTV	Surface to Surface	Army
PATRIOT	MIM-104A	Raytheon	Surface to Air	Army
ALCM	AGM-86A	Boeing	Air to Surface	Navy
SMII	RIM-66C	GD	Surface to Air	Navy

Data Normalization Steps

- Distributed fee, G&A, and COM across all WBS lines - fully loaded cost.
- Stripped nonrecurring costs.
- Stripped non-manufacturing (below the line items) from recurring manufacturing costs. These include such WBS lines as SE, PM, T&E, and data.
- Distributed manufacturing costs that could not be attributed to a single hardware item across all hardware items proportionally. Examples include recurring engineering and quality control.
- Converted TY costs to BY 2001 using BMDO 2000 inflation indices.
- Chose to include only the "**Missile as it flies**" components for this analysis.
- In some cases delivery quantities of HW items within a component differed. Normalized for quantity by:
  - Using the Guidance, Control, and Electronics quantity as base quantity (roughly 80% of cost).
  - Estimated T1s and LCs for the components having unequal quantities.
  - Calculated estimated costs of the hardware component for each lot using the GCE quantity.

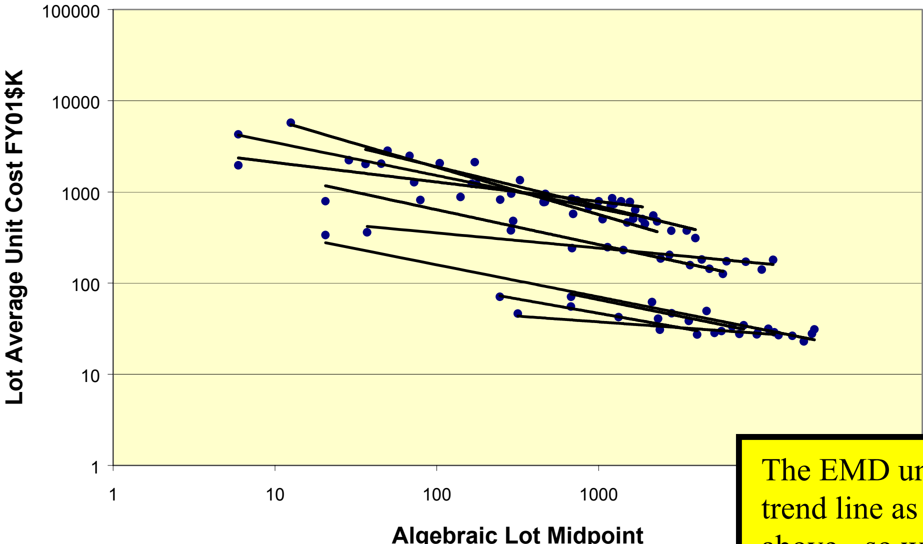
Data Plotted On a Log/Log Scale

EMD data is included, Count runs continuously from EMD Unit 1 through Production quantities

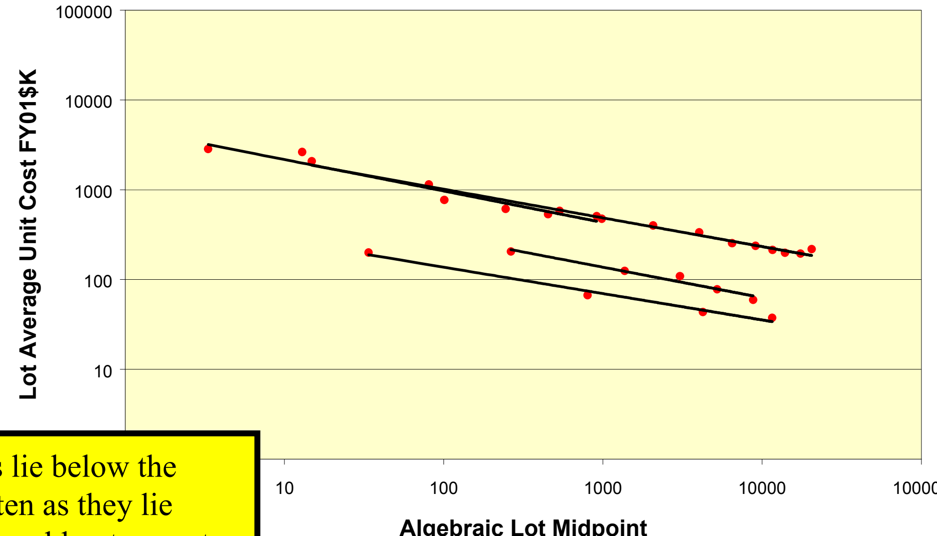


Data by Mission Area Class

Air to Air System Slopes

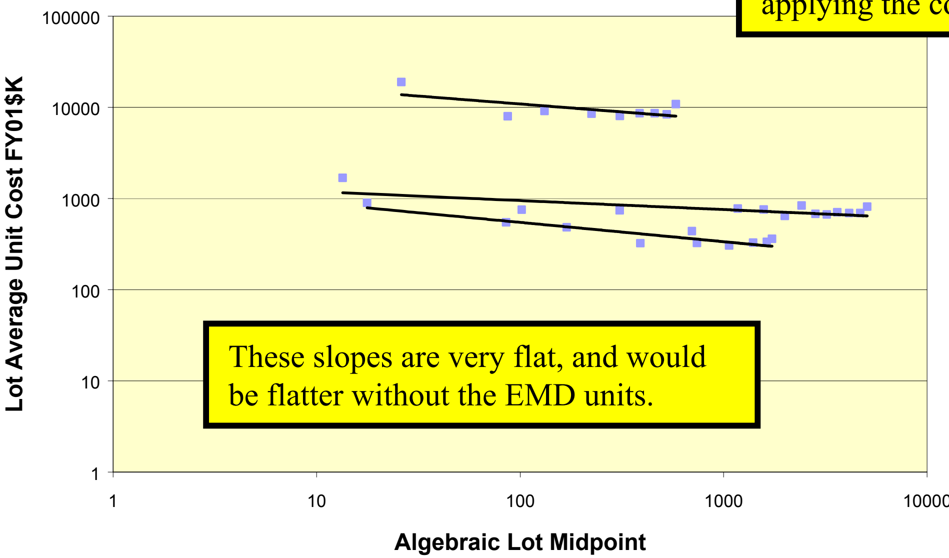


Air to Surface Missile Slopes



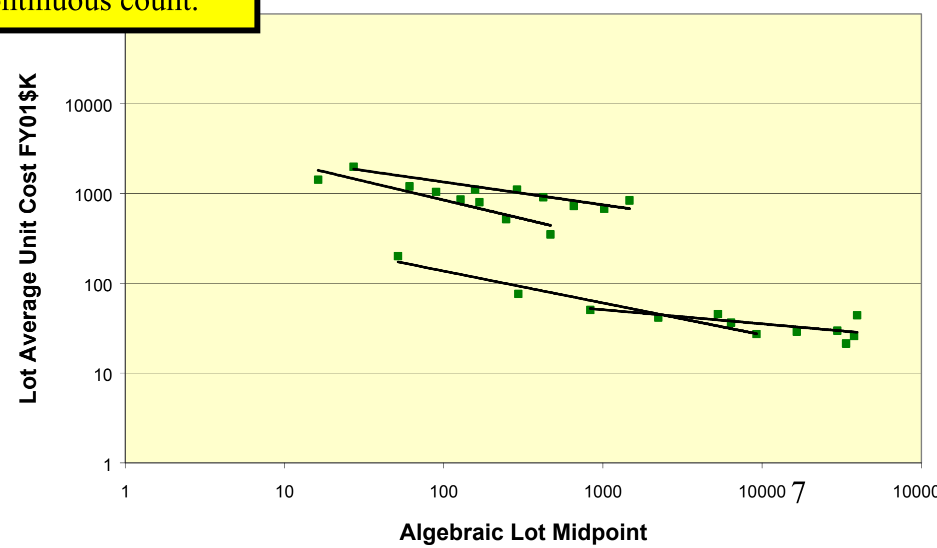
The EMD units lie below the trend line as often as they lie above - so we would not expect much of a step factor when applying the continuous count.

Surface to Surface Missile Slopes



These slopes are very flat, and would be flatter without the EMD units.

Surface to Air Missile Slopes



Single System, CAUC Results for Production (Pre-production Data Excluded)

CAUC Results by Mission Area					
System	Nomenclature	GCE Slope	AP Slope	WH Slope	TC Slope
Air to Air Systems					
AMRAAM	AIM-120	78.6%	85.4%	79.7%	78.9%
AMRAAM	AIM-120	78.3%	84.5%	73.9%	78.4%
PHOENIX	AIM-54A	79.1%	73.8%		78.4%
PHOENIX	AIM-54C	91.2%		88.8%	91.3%
SIDEWINDER	AIM-9L	80.2%			80.2%
SIDEWINDER	AIM-9L	81.4%			81.4%
SIDEWINDER	AIM-9M	88.4%			88.4%
SIDEWINDER	AIM-9M	85.3%			85.3%
SPARROW	AIM/RIM-7M	87.1%	80.7%		86.8%
SPARROW	AIM-7F	80.7%	87.0%		81.2%
Group Median		81.1%	84.5%	79.7%	81.3%
Air to Surface Systems					
ALCM	AGM-86A	77.1%	75.8%	80.1%	79.4%
HARM	AGM-88A/B	84.5%	77.8%	98.1%	83.7%
MAVERICK	AGM-65A/B	86.8%	85.8%	83.4%	86.3%
MAVERICK	AGM-65F	78.7%	87.4%		78.7%
Group Median		81.6%	81.8%	83.4%	81.6%
Surface to Air Systems					
PATRIOT	MIM-104A	93.8%	84.3%	81.5%	90.0%
SMII	RIM-66C	83.6%	87.5%		83.9%
STINGER	FIM-92A RMP	89.2%	85.1%		86.8%
STINGER	FIM-92A	86.9%	88.5%		87.6%
Group Median		88.1%	86.3%	81.5%	87.2%
Surface to Surface Systems					
ATACM	MGM-140	100.2%	98.3%	97.8%	99.6%
HARPOON	UGM-84	102.0%	131.7%	92.1%	101.2%
TRIDENT I	UGM-96A		101.5%	98.9%	101.0%
Group Median		101.1%	101.5%	97.8%	101.0%
Database Median		84.9%	85.6%	86.1%	85.3%

Differences between median Mission Area classes are apparent.

No apparent differences between component classes.

Using Indicator Variables in a Cost Improvement Model (ln/ln Model)

We start with the standard ln/ln model equation: $\ln(y) = b_0 + b_1 \ln(x) + \varepsilon$

If we introduce an indicator variable "D" to the equation the model generates another term: $\ln(y) = b_0 + b_1 \ln(x) + b_2 D + \varepsilon$

We can also introduce an interaction term between ln(x) and D by multiplying the variables producing another model term: $\ln(y) = b_0 + b_1 \ln(x) + b_2 D + b_3 D \ln(x) + \varepsilon$

Using algebra we can rearrange the variables: $\ln(y) = b_0 + b_2 D + (b_1 + b_3 D) \ln(x) + \varepsilon$

The exponential of both sides is: $y = e^{(b_0 + b_2 D + (b_1 + b_3 D)\ln(x) + \varepsilon)}$

Simple Algebra produces: $y = e^{b_0} e^{b_2 D} x^{(b_1 + b_3 D)} (error)$

- The addition of an Indicator variable produces a multiplicative adjustment to a T1. We use these to estimate system specific T1s and Step Factors.
- The addition of an interaction term between ln(x) and an indicator variable produces an additive change to the coefficient describing slope. We use these to estimate class specific slopes.

Combined CAUC Model for Production

Objectives:

- Find the best fitting combination of production learning curve and unit costs.
- Determine if apparent differences between Mission Class slopes are statistically significant

We start with the standard Cumulative Average Unit Cost Model:

$$Y = e^{b_0} * X^{b_1} * \varepsilon$$

Where:

$Y \equiv$ Cumulative Average Unit Cost for units 1 through X.

$e^{b0} \equiv$ Theoretical 1st Unit Cost

Learning Curve Slope $\equiv 2^{b1}$

$X \equiv$ Cumulative Quantity

$b_1 \equiv$ Exponent for cumulative quantity

$\varepsilon \equiv$ A multiplicative error term

We then add dummy variables (S_i) for each missile system (except the last) so that $S_i = 1$ if the system is system i, and 0 otherwise. This produces system specific T1s.

$$Y = (e^{b_0})(X^{b_1})(e^{\sum S_i b_{i+1}}) * \varepsilon = (e^{b_0 + \sum S_i b_{i+1}})(X^{b_1}) * \varepsilon$$

We add 3 dummy variables (M_j) for mission area (less Air to Air) so that $M_j = 1$ if the Mission Area is equal to M_j, -1 if an Air to Air system, and 0 otherwise. We multiply this variable by ln(X) to develop an interaction term that produces specific slopes for each mission area and enables testing them for a statistically significant difference from the sample average.

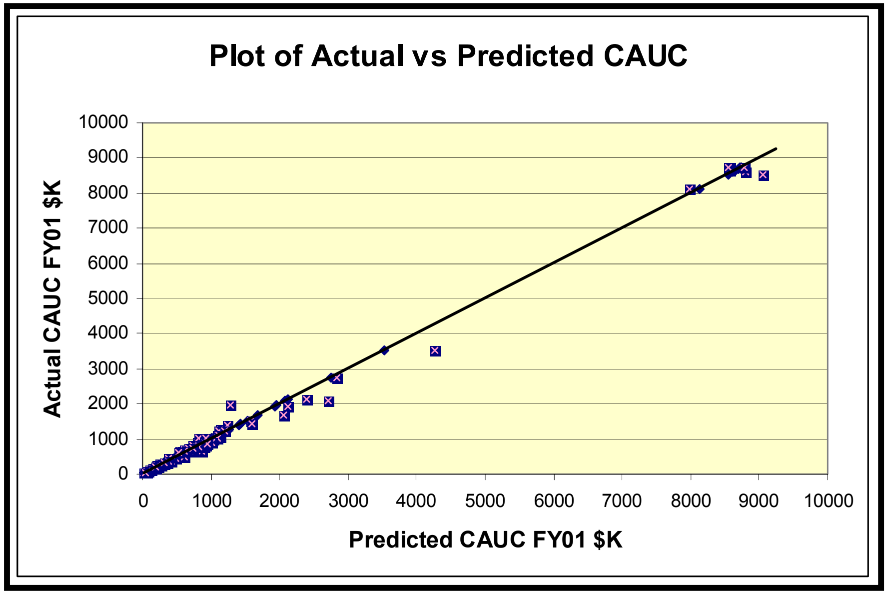
$$Y = (e^{b_0 + \sum S_i b_{i+1}})(X^{b_1})(X^{\sum M_j b_{21+j}}) * \varepsilon = (e^{b_0 + \sum S_i b_{i+1}})(X^{b_1 + \sum M_j b_{21+j}}) * \varepsilon$$

Production Model CAUC Slopes

Mission Area Class	5% Low	Slope	95% High	T-stat	P-value
Database Mean	87.0%	87.7%	88.5%	N/A	N/A
Air to Air	80.8%	82.2%	83.6%	-8.35	0.000
Air to Surface	81.1%	82.2%	83.3%	-9.46	0.000
Surface to Air	85.0%	86.8%	88.7%	-0.98	0.330
Surface to Surface	99.0%	101.0%	103.0%	14.21	0.000

Conclusions:

- The mean Air to Air, Air to Surface, and Surface to Surface class slopes are different from the database mean.
- Mission Area Class is an important criterion in selecting a CAUC slope



Single System, UT Results for Production (Pre-production Data Excluded)

Unit Theory Results by Mission Area						
System	Nomenclature	Mission	GCE	AP	WH	TC
Air to Air Systems						
AMRAAM	AIM-120	Air to Air	75.7%	83.7%	80.3%	76.1%
AMRAAM	AIM-120	Air to Air	77.7%	85.6%	73.3%	77.9%
PHOENIX	AIM-54A	Air to Air	80.3%	74.6%		79.5%
PHOENIX	AIM-54C	Air to Air	88.4%		104.9%	89.5%
SIDEWINDER	AIM-9L	Air to Air	79.6%			79.6%
SIDEWINDER	AIM-9L	Air to Air	80.6%			80.6%
SIDEWINDER	AIM-9M	Air to Air	91.1%			91.1%
SIDEWINDER	AIM-9M	Air to Air	84.8%			84.8%
SPARROW	AIM/RIM-7M	Air to Air	87.9%	78.5%		87.4%
SPARROW	AIM-7F	Air to Air	79.0%	85.5%		79.5%
Group Median			80.5%	83.7%	80.3%	80.1%
Air to Surface Systems						
ALCM	AGM-86A	Air to Surface	77.8%	80.5%	78.7%	78.6%
HARM	AGM-88A/B	Air to Surface	84.5%	69.0%	98.7%	83.0%
MAVERICK	AGM-65A/B	Air to Surface	87.0%	86.2%	84.3%	86.7%
MAVERICK	AGM-65F	Air to Surface	78.7%	87.4%		78.7%
Group Median			81.6%	83.4%	84.3%	80.9%
Surface to Air Systems						
PATRIOT	MIM-104A	Surface to Air	93.6%	80.7%	84.1%	90.5%
SMII	RIM-66C	Surface to Air	80.5%	84.8%		80.9%
STINGER	FIM-92A RMP	Surface to Air	90.5%	88.6%		89.0%
STINGER	FIM-92A	Surface to Air	85.2%	89.1%		87.0%
Group Median			87.9%	86.7%	84.1%	88.0%
Surface to Surface Systems						
ATACM	MGM-140	Surface to Surface	101.1%	102.5%	105.0%	101.7%
HARPOON	UGM-84	Surface to Surface	103.4%	137.4%	86.6%	102.4%
TRIDENT I	UGM-96A	Surface to Surface		102.1%	99.7%	101.4%
Group Median			102.3%	102.5%	99.7%	101.7%
Database Median			84.7%	85.6%	85.5%	84.8%

Differences between median Mission Area classes are apparent.

No apparent differences between component classes.

Combined UT Model for Production

Objectives:

- Find the best fitting combination of production learning curve and unit costs.
- Determine if apparent differences between Mission Class slopes are statistically significant

We start with the standard Unit Theory Model:

$$\boxed{Y = e^{b_0} * X^{b_1} * \varepsilon}$$

Where:

$Y \equiv$ Unit Cost for unit X.

$e^{b0} \equiv$ Theoretical 1st Unit Cost

Learning Curve Slope $\equiv 2^{b1}$

$X \equiv$ Xth unit produced

$b_1 \equiv$ Exponent for unit

$\varepsilon \equiv$ A multiplicative error term

We then add dummy variables (S_i) for each missile system (except the last) so that $S_i = 1$ if the system is system i, and 0 otherwise. This produces system specific T1s.

$$\boxed{Y = (e^{b_0})(X^{b_1})(e^{\sum S_i b_{i+1}}) * \varepsilon = (e^{b_0 + \sum S_i b_{i+1}})(X^{b_1}) * \varepsilon}$$

We add 3 dummy variables (M_j) for mission area (less Air to Air) so that $M_j = 1$ if the Mission Area is equal to M_j, -1 if an Air to Air system, and 0 otherwise. We multiply this variable by ln(X) to develop an interaction term that produces specific slopes for each mission area and enables testing them for a statistically significant difference from the sample average.

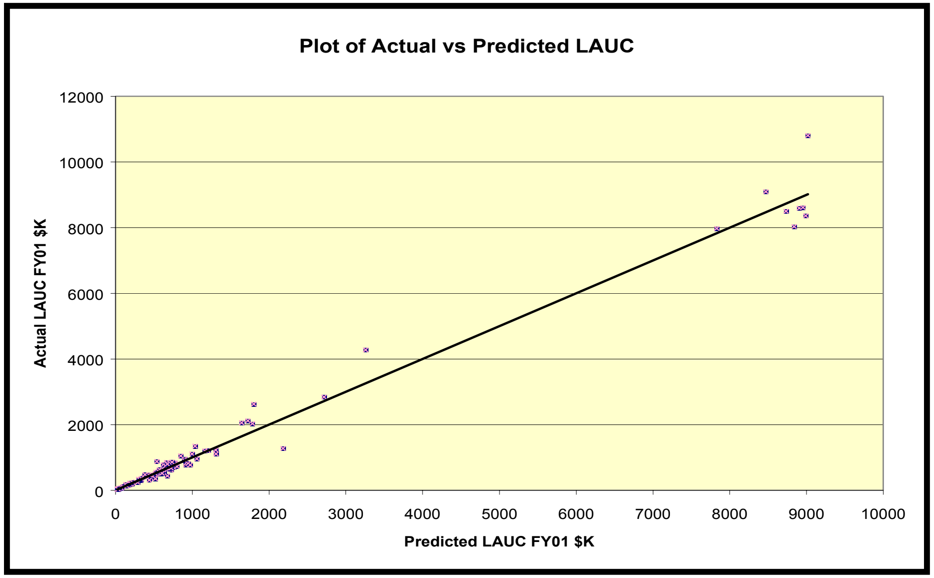
$$\boxed{Y = (e^{b_0 + \sum S_i b_{i+1}})(X^{b_1})(X^{\sum M_j b_{21+j}}) * \varepsilon = (e^{b_0 + \sum S_i b_{i+1}})(X^{b_1 + \sum M_j b_{21+j}}) * \varepsilon}$$

Production Model Unit Theory Slopes

Mission Area Class	5% Low	CI Slope	95% High	T-stat	P-value
Database Mean	86.4%	87.6%	88.7%	-	-
Air to Air	79.6%	81.7%	83.9%	-5.72	0.000
Air to Surface	79.1%	81.6%	84.2%	-6.68	0.000
Surface to Air	83.3%	86.7%	90.2%	-0.66	0.513
Surface to Surface	97.9%	101.8%	105.8%	9.78	0.000

Conclusions:

- The mean Air to Air, Air to Surface, and Surface to Surface class slopes are different from the database mean.
- Mission Area Class is an important criterion in selecting a Unit Theory slope



Single System, Rate Adjusted Results for Production (Pre-production Data Excluded)

UNIT w Rate Results by Mission Area									
System	Nomenclature	GCE		AP		WH		TC	
		Quantity	Rate	Quantity	Rate	Quantity	Rate	Quantity	Rate
Air to Air Systems									
AMRAAM	AIM-120	73.7%	108.4%	82.0%	106.4%	82.0%	94.0%	74.3%	107.9%
AMRAAM	AIM-120	85.8%	85.0%	88.3%	95.0%	86.3%	76.0%	86.0%	85.0%
PHOENIX	AIM-54A	88.2%	77.0%	79.1%	85.0%			86.9%	78.0%
PHOENIX	AIM-54C	91.8%	89.0%			108.4%	91.0%	93.1%	88.0%
SIDEWINDER	AIM-9L	82.5%	87.0%					82.5%	87.0%
SIDEWINDER	AIM-9L	85.3%	68.0%					85.3%	68.0%
SIDEWINDER	AIM-9M	90.9%	89.0%					90.9%	89.0%
SIDEWINDER	AIM-9M	84.2%	89.0%					84.2%	89.0%
SPARROW	AIM/RIM-7M	91.1%	88.0%	75.3%	117.0%			90.3%	89.0%
SPARROW	AIM-7F	80.0%	98.0%	79.5%	113.0%			80.0%	99.0%
Group Median		85.6%	88.5%	79.5%	106.4%	86.3%	91.0%	85.7%	88.5%
Air to Surface Systems									
ALCM	AGM-86A	101.1%	73.0%	179.2%	38.0%	94.5%	80.0%	96.3%	78.0%
HARM	AGM-88A/B	86.2%	96.3%	68.4%	101.8%	99.4%	98.6%	84.0%	97.6%
MAVERICK	AGM-65A/B	Insufficient data to develop rate adjusted CI.							
MAVERICK	AGM-65F	71.2%	134.5%	71.0%	182.7%			83.2%	89.0%
Group Median		86.2%	96.3%	71.0%	101.8%	97.0%	89.3%	84.0%	89.0%
Surface to Air Systems									
PATRIOT	MIM-104A	99.1%	88.0%	89.6%	77.0%	87.6%	91.0%	95.8%	88.0%
SMII	RIM-66C	94.3%	78.0%	99.6%	78.0%			94.7%	78.0%
STINGER	FIM-92A RMP	88.4%	89.2%	84.6%	79.4%			86.3%	86.0%
STINGER	FIM-92A	83.1%	105.0%	99.7%	93.0%			87.5%	99.0%
Group Median		91.4%	88.6%	94.6%	78.7%	87.6%	91.0%	91.1%	87.0%
Surface to Surface Systems									
ATACM	MGM-140	99.4%	97.0%	98.1%	92.0%	99.5%	90.0%	99.2%	95.0%
HARPOON	UGM-84	105.3%	75.5%	137.9%	94.8%	90.4%	73.4%	104.3%	76.3%
TRIDENT I	UGM-96A			103.0%	99.0%	95.6%	86.0%	102.0%	99.0%
Group Median		102.4%	86.3%	103.0%	94.8%	95.6%	86.0%	102.0%	95.0%
Database Median		88.2%	89.0%	88.3%	94.8%	94.5%	90.0%	87.2%	88.5%

Many systems have illogical rate adjusted results - the quantity and/or rate slopes are not believable. This is largely due covariance between the quantity and rate variables.

Although median values are shown in the table, we don't believe they have much usefulness.

Combined Rate Model for Production

Objectives:

- Find the best fitting combination of production learning curve, rate adjustment, and unit costs.
- It would be nice if they were also believable and explainable.

We start with the model we used for Unit Theory analysis and add a rate term:

$$Y = (e^{b_0 + \sum S_i b_{i+1}})(X^{b_1 + \sum M_j b_{21+j}})(R^{b_{25}}) * \varepsilon$$

Where:
R ≡ Manufacturing Quantity/Delivery Period (usually the annual lot quantity)
b_{25} ≡ Exponent for the Rate Slope ≡ 2^{b25}

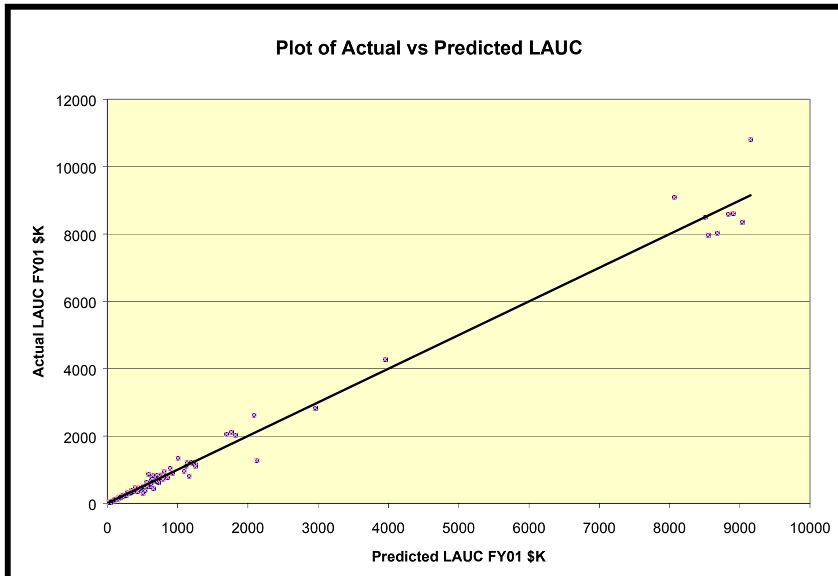
Then we add interaction terms by multiplying M_j by ln(R) to produce specific rate slopes for each mission area.

$$Y = (e^{b_0 + \sum S_i b_{i+1}})(X^{b_1 + \sum M_j b_{21+j}})(R^{b_{25} + \sum M_j b_{25+j}}) * \varepsilon$$

Production Model Rate Adjusted Slopes

Type Slope	5% Low	Value	95% High	T-stat	P-value
DB Average Rate	88.0%	90.5%	93.1%	-5.85	0.000
Air to Air Rate	80.6%	85.3%	90.2%	-2.43	0.017
Air to Surface Rate	84.9%	91.6%	98.7%	0.31	0.755
Surface to Air Rate	84.9%	89.1%	93.4%	-0.61	0.540
Surface to Surface Rate	91.3%	96.6%	102.1%	2.21	0.029
DB Average Qty	89.8%	91.4%	93.0%	-8.38	0.000
Air to Air Qty	85.2%	88.3%	91.4%	-2.62	0.010
Air to Surface Qty	81.0%	85.4%	90.0%	-2.75	0.007
Surface to Air Qty	87.4%	90.2%	93.2%	-0.73	0.466
Surface to Surface Qty	99.6%	102.6%	105.8%	6.89	0.000

- Rate slopes and quantity slopes are believable.
- Air to Air and Surface to Surface rate slopes are not equal to the database average.
- Air to Air, Air to Surface, and Surface to Surface quantity slopes are not equal to the database average.
- Again, mission area class is an important consideration.



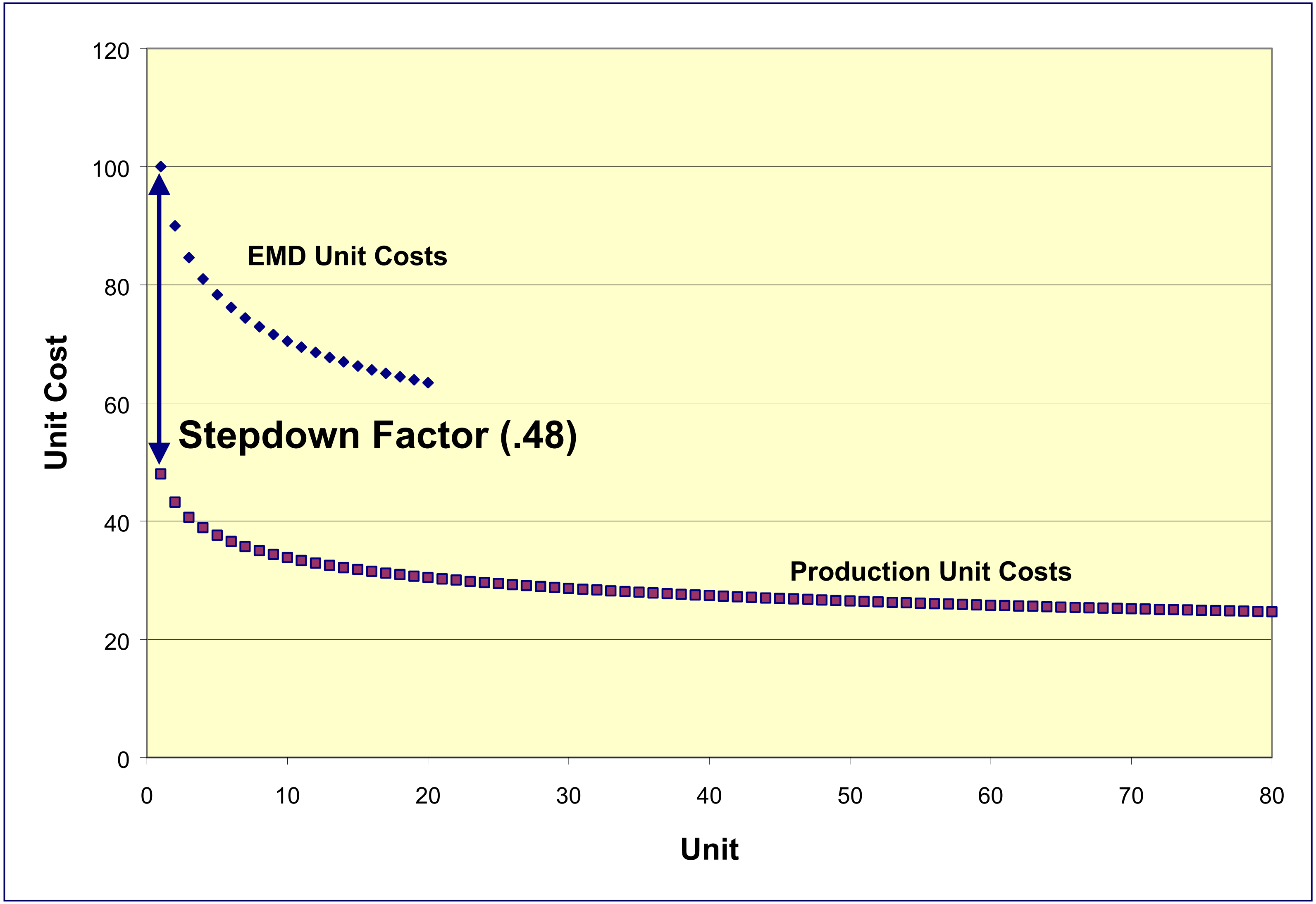
Including EMD Data in the Analysis

- Caution: No matter how we treat it, adding EMD manufacturing to the Production data set increases variability in the prediction models.
- In most cases, there is only one EMD contract and costs are reported as total for all of the delivered missiles (One data point per system).
- We are interested in this because traditional estimating methodologies use "Step Factors" and "Learning Curve Adjustments" to estimate EMD recurring costs given a production unit cost and/or to estimate production costs using "actuals" collected during EMD.

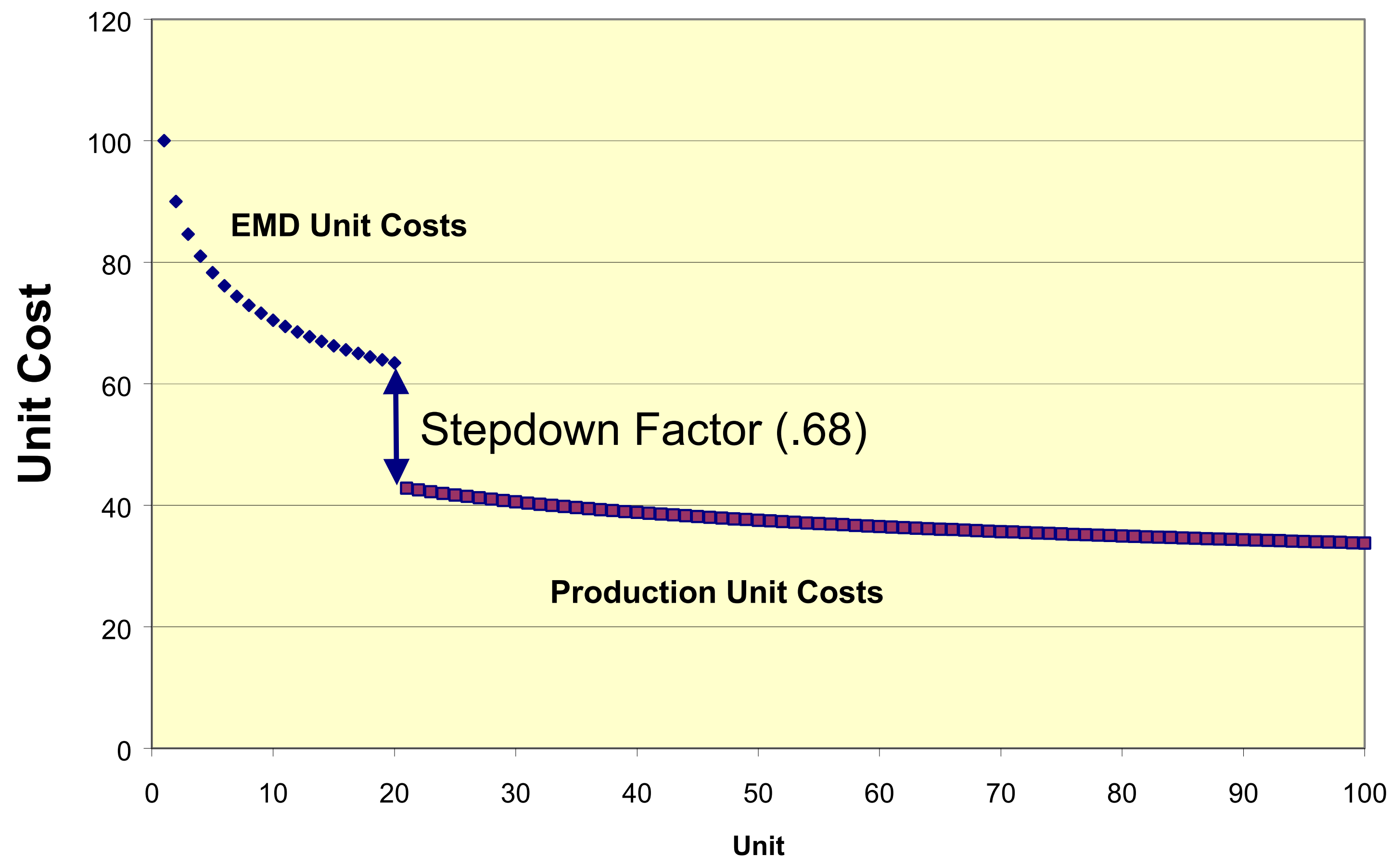
EMD-Production Curve Fitting Issues

- We have a limited number of EMD data points - not enough to find Mission Area Class specific step factors and cost improvement slope changes for EMD manufacturing.
  - We opted to find a single best fitting step factor and slope change for the data set.
  - None of the slope change terms were statistically significant - not enough data to derive it.
- The production count can be modeled as continuous from EMD unit 1 through Production or by resetting the count to 1 at the first Production unit.
  - **We did it both ways!**
- Interim (LRIP, Pilot Production, and Qualification Production) Lots muddy the distinction between Production and EMD.
  - They can be modeled either as the first Production lot or as second EMD lot.
    - Step Factor is applied either before or after the interim lot.
    - Learning curve change is applied either before or after the interim lot.
    - If the count resets, it is applied either before or after the interim lot.
  - **We did it both ways!**
- End result is we have four models for each type theory (UT, CAUC, Rate)

Unit Theory Reset Model



Unit Theory Continuous Model



Adding a Step Factor to the model (Using CAUC for Demonstration)

Objectives:

Find the best fitting relationship between $T1_P$ and $T1_{EMD}$. $T1_{EMD} = T1_P(SF)$

Demonstrating with the CAUC Model, our model using production data only was:

$$\boxed{Y = (e^{b_0 + \sum S_i b_{i+1}})(X^{b_1 + \sum M_j b_{21+j}}) * \varepsilon}$$

We include the EMD data points and then add a dummy variable (E) that takes on a value of 1 for an EMD data point and 0 for a Production data point. This changes our prediction equation to

$$\begin{aligned} Y &= (e^{b_0 + \sum S_i b_{i+1}})(X^{b_1 + \sum M_j b_{21+j}})(e^{E b_{26}}) * \varepsilon \\ &= (e^{b_0 + \sum S_i b_{i+1} + E b_{26}})(X^{b_1 + \sum M_j b_{21+j}}) * \varepsilon \end{aligned}$$

and the estimated Step Factor is

$\boxed{SF = e^{b_{26}}}$ where $\boxed{T1_{EMD} = e^{b_{26}} T1_P}$

Adding a Slope Change to the Model (Using CAUC for Demonstration)

Objectives:

Find the best fitting estimates for production slope and the EMD slope

We can do this by adding an interaction term - the multiplication of the EMD dummy variable by the natural logarithm of X. When we introduce this variable the prediction equation becomes.

$$Y = (e^{b_0 + \sum S_i b_{i+1} + E b_{26}})(X^{b_1 + \sum M_j b_{21+j}})(X^{E b_{27}}) * \varepsilon$$

$$= (e^{b_0 + \sum S_i b_{i+1} + E b_{26}})(X^{b_1 + \sum M_j b_{21+j} + E b_{27}}) * \varepsilon$$

The estimated overall CAUC slope during production is then 2^{b_1}

The estimated overall CAUC slope during EMD is then $2^{b_1 + b_{27}}$

Treatment of LRIP Units:

- Setting the EMD dummy variable to “0” for LRIP Lots treats LRIP as a Production Lot
- Setting the EMD dummy variable to “1” for LRIP Lots treats LRIP as a subsequent EMD Lot

Although we built models that include this interaction term, the coefficients were not statistically significant and we later dropped this term.

CAUC Model Results

Model Type	Lots Assigned as EMD	Adjusted R^2	Standard Error	% SE	% Bias
Continuous	EMD only	0.973	495	15.0%	-0.9%
Continuous	EMD + LRIP	0.977	459	14.7%	-0.9%
Reset	EMD only	0.906	708	16.9%	-1.1%
Reset	EMD + LRIP	0.922	660	18.7%	-0.5%

Model Type	Lots Assigned as EMD	A-A Slope	A-S Slope	S-A Slope	S-S Slope	Average Slope	Step Down Factor	Step Factor P-Value
Continuous	EMD only	79.6%	79.6%	79.1%	85.9%	81.0%	1.08	0.256
Continuous	EMD + LRIP	80.5%	80.2%	80.3%	87.5%	82.1%	0.94	0.364
Reset	EMD only	82.2%	82.2%	84.4%	94.4%	85.7%	0.75	0.014
Reset	EMD + LRIP	83.6%	82.4%	84.8%	96.4%	86.6%	0.71	0.007

- Models show that taking step factors and resetting the count after LRIP provide better fits than doing so before LRIP.
- LRIP is more representative of EMD than Production Phase manufacturing.

- Continuous Models are clearly stronger than the reset models.
- Step Factors are not significant for the continuous models.

Unit Theory Results

Model Type	Lots Assigned as EMD	Adjusted R^2	Standard Error	% SE	% Bias
Continuous	EMD only	0.914	695	24.2%	-2.3%
Continuous	EMD + LRIP	0.929	636	23.9%	-2.3%
Reset	EMD only	0.909	709	23.1%	-2.1%
Reset	EMD + LRIP	0.941	581	22.7%	-2.0%

Model Type	Lots Assigned as EMD	A-A Slope	A-S Slope	S-A Slope	S-S Slope	Average Slope	Step Down Factor	Step Factor P-Value
Continuous	EMD only	79.6%	79.8%	81.0%	90.9%	82.7%	0.95	0.595
Continuous	EMD + LRIP	80.7%	80.3%	82.1%	93.0%	84.0%	0.84	0.080
Reset	EMD only	81.6%	81.5%	84.4%	95.4%	85.5%	0.75	0.008
Reset	EMD + LRIP	83.3%	82.0%	85.2%	98.1%	86.9%	0.67	0.001

- Models show that taking step factors and resetting the count after LRIP provide better fits than doing so before LRIP.
- LRIP is more representative of EMD than Production Phase manufacturing.

- A reset model provides the best statistical fit.
- The step factor for this model is statistically significant.

Bill Seeman's Favorite Unit Theory Model

- **No Step Factor with a continuous count**

Model Type	Lots Assigned as EMD	Adjusted R^2	Standard Error	% SE	% Bias
Continuous	EMD only	0.910	708	24.1%	-2.3%

A-A Slope	A-S Slope	S-A Slope	S-S Slope	Average Slope	Step Factor
79.1%	79.9%	81.2%	90.5%	82.6%	1.00

- Step Factor Term is removed from the model – thus forcing it to 1.0.
- Slopes change very little as the original step factor value was 0.95

Rate Adjusted Results

Model Type	Lots Assigned as EMD	Adjusted R^2	Standard Error	% SE	% Bias
Continuous	EMD only	0.860	874	21.2%	-1.8%
Continuous	EMD + LRIP	0.878	818	20.9%	-1.8%
Reset	EMD only	0.847	914	21.1%	-1.8%
Reset	EMD + LRIP	0.892	769	20.8%	-1.7%

Model Type	Lots Assigned as EMD	A-A Q/R	A-S Q/R	S-A Q/R	S-S Q/R	Average Q/R	Step Down Factor	SF P-value
Continuous	EMD only	85.0%	84.6%	86.0%	92.3%	87.0%	1.09	0.375
		87.3%	91.8%	88.5%	94.0%	90.3%		
Continuous	EMD + LRIP	85.2%	84.3%	86.6%	93.0%	87.3%	1.00	0.958
		87.8%	92.8%	88.9%	94.2%	90.8%		
Reset	EMD only	84.9%	85.5%	88.9%	98.4%	89.2%	0.87	0.127
		91.3%	92.7%	89.3%	90.9%	91.1%		
Reset	EMD + LRIP	85.8%	84.9%	89.2%	100.7%	89.9%	0.77	0.016
		91.9%	94.3%	90.2%	90.6%	91.7%		

Like Unit Theory, the Reset model with LRIP treated as a second EMD lot provides the best fit.

Bill's Favorite Rate Adjusted Model

• **No Step Factor with a continuous count**

Model Type	Lots Assigned as EMD	Adjusted R^2	Standard Error	% SE	% Bias
Continuous	EMD Only	0.881	807.1	20.8%	-1.8%

	A-A	A-S	S-A	S-S	Average	SF
Quantity	85.1%	84.5%	86.9%	92.9%	87.3%	1.00
Rate	87.7%	92.7%	88.8%	94.4%	90.9%	

Since our step factor was nearly 1.00 in the unconstrained mode, this model changes the parameters very little.

Why We Like the MDA Study

- We can track the analysis back to the source data.
- The study is based on CCDRs – the official government way of collecting cost data.
- We can explain all adjustments performed to the data.
  - We know why they were done.
  - We can reproduce them
  - We can change them
- Learning Curves are based on quantitative analysis using many systems.
  - No gut feelings
  - No we've always used this - and it works
  - Not based on contractor statements/proposals
  - Is not based reliant on analogy to a single program
- Model statistics show strong relationships.
- Model coefficients make sense.
- We believe that the MDA methodologies should be used until compelling evidence leads us to a different method.

An Example Problem Showing How We Apply the MDA Study to EMD

- Lets assume we have collected and normalized data on manufacturing costs for 30 EMD missiles and we want to estimate manufacturing costs for 250 production units.
  - The total cost for 30 missiles is $183 million in constant FY02 $.
  - The delivery window for the 30 EMD units was 2.5 years.
  - The production delivery schedule is 25, 50, 75, 75, 25.
  - We will use Bill’s favorite model forms for unit theory and rate adjusted cost improvement.
  - We will also use the database average slopes – rather than a class average for this example (we normally use several methods to develop a range).

Unit Theory Method

- First we develop the quantity exponent for the LC slope 82.6%.

$$b = \frac{\ln(.826)}{\ln(2)} = -.276$$

- Then we develop the theoretical first unit cost using Simpson's approximation.

$$T1 = \frac{EMD_{Cum}}{\frac{(LU+.5)^{b+1}}{b+1} - \frac{(FU-.5)^{b+1}}{b+1}} = \frac{183}{\frac{(30.5)^{.724}}{.724} - \frac{(.5)^{.724}}{.724}} = 11.75$$

- Then we use the apply Simpson's approximation to estimate total production cost -with no step factor.

$$Cost_{\Pr od} = T1\left(\frac{(LU+.5)^{b+1}}{b+1} - \frac{(FU-.5)^{b+1}}{b+1}\right) = 11.75\left(\frac{(280.5)^{.724}}{.724} - \frac{(30.5)^{.724}}{.724}\right) = 768.8$$

Rate Adjusted Method

- First we develop the exponents for both quantity slope and rate slope. $b_1 = \frac{\ln(.873)}{\ln(2)} = -.196$ $b_2 = \frac{\ln(.909)}{\ln(2)} = -.138$

- Then we apply Simpson's approximation with rate term to develop a rate adjusted T1 (T1R1).

$$T1 = \frac{EMD_{Cum}}{\left(\frac{(LU+.5)^{b_1+1}}{b_1+1} - \frac{(FU-.5)^{b_1+1}}{b_1+1}\right)R^{b_2}} = \frac{183}{\left(\frac{(30.5)^{.804}}{.804} - \frac{(.5)^{.804}}{.804}\right)\left(\frac{30}{2.5}\right)^{-.138}} = 13.78$$

- Then we calculate the production costs one lot at a time, applying the appropriate rate and sum them.

$$Cost_{\Pr od} = \sum T1\left(\frac{(LU+.5)^{b_1+1}}{b_1+1} - \frac{(FU-.5)^{b_1+1}}{b_1+1}\right)\left(R^{b_2}\right) = 765.8$$

Then We Reconcile and Apply Programmatics

- The $769M and $766M results are nearly equal so it doesn't much matter which methodology we apply. We can develop a range of expected outcomes be applying several of the cost improvement methodologies provided in the study.
- We apply judgement based on similarity of the program to our database to decide which model form is most applicable.
- Then we look at the program itself. Since our model parameters are the expected values across all missile programs – where does this program compare to the average? For example:
  - Will fee and cost reductions be greater than normal?
  - Is there a greater than normal reduction in touch labor at transition between EMD and Production?
  - Are there components on the EMD missiles that are not required on the production missiles?
- This is where we apply the art in cost estimating. Answers to these questions could drive including a step factor and possibly justify modifications to the slopes.

Observations on Other Cost Improvement Studies

- We are frequently uncertain what data was used and of its quality
- We don’t have the data sets
  - Can not validate accuracy
  - Can not manipulate assumptions or model forms
- Limited model statistics are provided.
- We’re sure there are other good studies out there – but we’re not sure which ones they are.

Questions??